Incidences between points and lines on a two-dimensional variety[*]

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Abstract

We present a direct and fairly simple proof of the following incidence bound: Let P be a set of m points and L a set of n lines in $\mathbb{R}^d$, for $d \geq 3$, which lie in a common algebraic two-dimensional surface of degree D that does not contain any 2-flat, so that no 2-flat contains more than $s \leq D$ lines of L. Then the number of incidences between P and L is

$$I(P,L) = O\left(m^{1/2}n^{1/2}D^{1/2} + m^{2/3}\min\{n, D^2\}^{1/3}s^{1/3} + m + n\right).$$

When $d = 3$, this improves the bound of Guth and Katz [11] for this special case, when d is not too large.

A supplementary feature of this work is a review, with detailed proofs, of several basic (and folklore) properties of ruled surfaces in three dimensions.

1 Introduction

Let P be a set of m distinct points and L a set of n distinct lines in $\mathbb{R}^d$. Let $I(P, L)$ denote the number of incidences between the points of P and the lines of L; that is, the number of pairs (p, ℓ) with $p \in P$, $\ell \in L$, and $p \in \ell$. If all the points of P and all the lines of L lie in a common 2-flat, then the classical Szemerédi–Trotter theorem [24] yields the worst-case tight bound

$$I(P,L) = O\left(m^{2/3}n^{2/3} + m + n\right). \tag{1}$$

This bound clearly also holds in $\mathbb{R}^d$, for any d, by projecting the given lines and points onto some generic 2-flat. Moreover, the bound will continue to be worst-case tight by placing all the points and lines in a common 2-flat, in a configuration that yields the planar lower bound.

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In the 2010 groundbreaking paper of Guth and Katz [11], an improved bound has been derived for $I(P, L)$, for a set P of m points and a set L of n lines in $\mathbb{R}^3$, provided that not too many lines of L lie in a common plane. Specifically, they showed:[1]

Theorem 1 (Guth and Katz [11]). *Let P be a set of m distinct points and L a set of n distinct lines in $\mathbb{R}^3$, and let $s \leq n$ be a parameter, such that no plane contains more than s lines of L. Then*

$$I(P, L) = O\left(m^{1/2}n^{3/4} + m^{2/3}n^{1/3}s^{1/3} + m + n\right).$$

This bound (or, rather, an alternative formulation thereof) was a major step in the derivation of the main result of [11], which was an almost-linear lower bound on the number of distinct distances determined by any finite set of points in the plane, a classical problem posed by Erdős in 1946 [6]. Guth and Katz's proof uses several nontrivial tools from algebraic and differential geometry, most notably the Cayley–Salmon theorem on osculating lines to algebraic surfaces in $\mathbb{R}^3$, and various properties of ruled surfaces. All this machinery comes on top of the major innovation of Guth and Katz, the introduction of the *polynomial partitioning technique.*

In this study, in contrast with the aforementioned work of Guth and Katz [11], and with the follow-up studies of Guth [9] and of Sharir and Solomon [20], we do not need to explicitly use the polynomial partitioning method, because we assume that the points and lines all lie in a common surface of degree D, making the polynomial partitioning step superfluous. Concretely, our main result is a simple and mostly elementary derivation of the following result.

Theorem 2. *Let P be a set of m distinct points and L a set of n distinct lines in $\mathbb{R}^d$, and let $2 \leq s \leq D$ be two integer parameters, so that all the points and lines lie in a common two-dimensional algebraic variety V of degree D that does not contain any 2-flat, and so that no 2-flat contains more than s lines of L. Then*

$$I(P, L) = O\left(m^{1/2}n^{1/2}D^{1/2} + m^{2/3}\min\{n, D^2\}^{1/3}s^{1/3} + m + n\right). \qquad (2)$$

We assume in the theorem that s is at most D, but in fact this assumption is superfluous and can be dropped. Indeed, for any 2-flat π, the intersection $\pi \cap V$ is a one-dimensional plane algebraic curve of degree D in π (this holds since V does not contain any 2-flat), and can therefore contain at most D lines.

We also have the following easy and interesting corollary.

Corollary 3. *Let P be a set of m distinct points and L a set of n distinct lines in $\mathbb{R}^d$, such that all the points and lines lie in a common two-dimensional algebraic variety of constant degree that does not contain any 2-flat. Then $I(P, L) = O(m + n)$, where the constant of proportionality depends on the degree of the surface.*

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[1] We skip over certain subtleties in their bound: They also assume that no *regulus* contains more than $s = \sqrt{n}$ input lines, but then they are able also to bound the number of intersection points of the lines. Moreover, if one also assumes that each point is incident to at least three lines then the term m in the bound can be dropped.

For $d = 3$, the corollary is not really new, because it can also be derived from the analysis in Guth and Katz [11], using a somewhat different approach. Nevertheless, we are not aware of any previous explicit statement of the corollary, even in three dimensions. As a matter of fact, the corollary can also be extended (with a different bound though) to the case where the containing surface may have planar components. See a remark to that effect at the end of the paper.

The significance of Theorem 2 is threefold:

(a) In three dimensions, the bound improves the Guth–Katz bound when $D \ll n^{1/2}$, for two-dimensional varieties V that do not contain planes. Note that the threshold $n^{1/2}$ is quite large—it is in fact larger than the standard degree $O(m^{1/2}/n^{1/4})$ used in the analysis of Guth and Katz [11] when $m \ll n^{3/2}$. We do not know how to extend our results (or whether such an extension is at all possible) to the case where V does contain planes.

(b) Another significant feature of our bound is that it does not contain the term nD, which arises naturally in [11] and other works, and seems to be unavoidable when P is an arbitrary set of points. See an additional discussion of this feature at the end of the paper.

(c) It offers a sharp point-line incidence bound in arbitrary dimensions, for the special case assumed in the theorem.

This paper is a step towards the study of point-line incidences on arbitrary varieties, rather than just in $\mathbb{R}^d$ (or $\mathbb{C}^d$). Moreover, as has been our experience, the study of incidences in d-space quickly reduces to questions about incidences within lower-dimensional varieties, and tools for analyzing incidences of this sort are very much in demand.

The analysis in this paper has indeed been used, as one of the key tools, in the analysis in our companion paper [22] on incidences between points and lines in four dimensions. In this application, the lack of the term nD is a crucial feature of our result, which was required in the scenario considered in [22].

The analysis in this paper makes extensive use of several properties of ruled surfaces in $\mathbb{R}^3$ or in $\mathbb{C}^3$. While these results exist as folklore in the literature, we include here detailed and rigorous proofs thereof, making them more accessible to the combinatorial geometry community.

2 Proof of Theorem 2

In most of the analysis in this section, we will consider the case $d = 3$. The reduction from an arbitrary dimension to $d = 3$ will be presented at the end of the section.

2.1 Preliminaries: Ruled surfaces

The proof is based on several technical lemmas that establish various properties of lines contained in an algebraic surface in three dimensions. Some of them are also mentioned in our companion study [22] on point-line incidences in four dimensions, while others present basic properties of ruled surfaces that are considered folklore in the literature. Having failed to find rigorous proofs of these properties, we provide here such proofs for the sake of completeness.

Singularity and flatness. The notion of singularities is a major concept, treated in full generality in algebraic geometry (see, e.g., Kunz [16, Theorem VI.1.15] and Cox et al. [3]), here we only recall some of their properties, and only for a few special cases that are relevant to our analysis.

Let V be a two-dimensional variety in $\mathbb{R}^3$ or $\mathbb{C}^3$, given as the zero set $Z(f)$ of some trivariate polynomial f. Assuming f to be square-free, a point $p \in Z(f)$ is *singular* if $\nabla f(p) = 0$. For any point $p \in Z(f)$, let

$$f(p + x) = f_\mu(x) + f_{\mu+1}(x) + \ldots$$

be the Taylor expansion of f near p, where f_j is the j-th order term in the expansion (which is a homogeneous polynomial of x degree j), and where we assume that there are no terms of order (i.e., degree) smaller than μ. In general, we have $f_1(x) = \nabla f(p) \cdot x$, $f_2(x) = \frac{1}{2} x^T H_f(p) x$, where H_f is the Hessian matrix of f, and the higher-order terms are similarly defined, albeit with more involved expressions.

If p is singular, we have $\mu \geq 2$. In this case, we say that p is a singular point of $Z(f)$ of *multiplicity* μ. For any point $p \in Z(f)$, we call the hypersurface $Z(f_\mu)$ the *tangent cone* of $Z(f)$ at p, and denote it by $C_p Z(f)$. If $\mu = 1$, then p is non-singular and the tangent cone coincides with the (well-defned) tangent plane $T_p Z(f)$ to $Z(f)$ at p. We denote by V_{sing} the locus of singular points of V. This is a subvariety of dimension at most one; see, e.g., Solymosi and Tao [23, Proposition 4.4].

Similarly, let γ be a one-dimensional algebraic curve in $\mathbb{R}^2$ or in $\mathbb{C}^2$, specified as $Z(f)$, for some bivariate square-free polynomial f. Then $p \in Z(f)$ is *singular* if $\nabla f(p) = 0$. The *multiplicity* μ of a point $p \in \gamma$ is defined as in the three-dimensional case, and we denote it as $\mu_\gamma(p)$; the multiplicity is at least 2 when p is singular. The singular locus γ_{sing} of γ is now a discrete set. Indeed, the fact that f is square-free guarantees that f has no common factor with any of its first-order derivatives, and Bézout's Theorem (see, e.g., [3, Theorem 8.7.7]) then implies that the common zero set of f, f_x, f_y, and f_z is a (finite) discrete set.

By Bézout's Theorem, a line ℓ can intersect at most D points of γ, *counted with multiplicities.* To define this concept formally, as in, e.g., Beltrametti [2, Section 3.4], let ℓ be a line and let $p \in \ell \cap \gamma$, such that ℓ is not contained in the tangent cone of γ at p. The *intersection multiplicity* of γ and ℓ at p is the smallest order of a nonzero term of the Taylor expansion of f at p in the direction of ℓ. The intersection multiplicity is also equal to $\mu_\gamma(p)$ (informally, this is the number of branches of γ that ℓ crosses at p, counted with multiplicity; see [3, Section 8.7] for a treatment on the intersection multiplicity in the plane).

We say that a line ℓ is a *singular line* for V if all of its points are singular points of V. By Guth and Katz [10] (see also Elekes et al. [5, Corollary 2]), the number of singular lines contained in V is at most $\deg(V)(\deg(V) - 1)$.

Assume that $V = Z(f)$ is an irreducible algebraic surface. We say that a non-singular point $x \in V$ is *flat* if the second-order Taylor expansion of f at x vanishes on the tangent plane $T_x V$, or alternatively, if the *second fundamental form* of V vanishes at x (see, e.g., Pressley [17]). Following Guth and Katz [10], Elekes et al. [5, Proposition 6] proved that a non-singular point $x \in V$ is flat if and only if certain three polynomials, each of degree at most $3\deg(V) - 4$, vanish at p. A non-singular line ℓ is said to be *flat* if all of its non-singular points are flat. By Guth and Katz [10] (see also Elekes et al. [5, Proposition 7]), the number of flat lines fully contained in V is at most $3\deg(V)^2 - 4\deg(V)$.

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Ruled surfaces. For a modern approach to ruled surfaces, there are many references; see, e.g., Hartshorne [13, Section V.2], or Beauville [1, Chapter III]; see also Salmon [18] and Edge [4] for earlier treatments of ruled surfaces. We say that a real (resp., complex) surface V is *ruled by real* (resp., *complex*) *lines* if every point p in a Zariski-open[2] dense subset of V is incident to a real (complex) line that is fully contained in V. This definition has been used in several recent works, see, e.g., [11, 15]; it is a slightly weaker condition than the classical condition where it is required that *every* point of V be incident to a line contained in V (e.g., as in [18]). Nevertheless, similarly to the proof of Lemma 3.4 in Guth and Katz [11], a limit argument implies that the two definitions are in fact equivalent. We give, in Lemma 11 below, a short algebraic proof of this fact, for the sake of completeness.

We first recall the classical theorem of Cayley and Salmon. Consider a polynomial $f \in \mathbb{C}[x, y, z]$ of degree $D \geq 3$. A *flecnode* of f is a point $p \in Z(f)$ for which there exists a line that passes through p and *osculates* to $Z(f)$ at p to order three. That is, if the direction of the line is v then $f(p) = 0$, and $\nabla_v f(p) = \nabla_v^2 f(p) = \nabla_v^3 f(p) = 0$, where $\nabla_v f, \nabla_v^2 f, \nabla_v^3 f$ are, respectively, the first, second, and third-order derivatives of f in the direction v (compare with the definition of singular points, as reviewed earlier, for the explicit forms of $\nabla_v f$ and $\nabla_v^2 f$). The *flecnode polynomial* of f, denoted FL_f, is the polynomial obtained by eliminating v from these three equations. As shown in Salmon [18, Chapter XVII, Section III], the degree of FL_f is at most $11D - 24$. By construction, the flecnode polynomial of f vanishes on all the flecnodes of f, and in particular on all the lines fully contained in $Z(f)$.

(Note that the correct formulation of Theorem 4 is over $\mathbb{C}$; earlier applications, over $\mathbb{R}$, as the one in Guth and Katz [11], require some additional arguments to establish their validity; see Katz [14] for a discussion of this issue.)

Theorem 4 (Cayley and Salmon [18]). *Let $f \in \mathbb{C}[x, y, z]$ be a polynomial of degree $D \geq 3$. Then $Z(f)$ is ruled by (complex) lines if and only if $Z(f) \subseteq Z(\mathsf{FL}_f)$.*

Lemma 5. *Let $f \in \mathbb{C}[x, y, z]$ be an irreducible polynomial such that there exists a nonempty Zariski open dense set in $Z(f)$ so that each point in the set is incident to a line that is fully contained in $Z(f)$. Then FL_f vanishes identically on $Z(f)$, and $Z(f)$ is ruled by lines.*

Proof. Let $U \subset Z(f)$ be the set assumed in the lemma. By assumption and definition, FL_f vanishes on U, so U, and its Zariski closure, are contained in $Z(f, \mathsf{FL}_f)$. Since U is open, it must be two-dimensional. Indeed, otherwise its complement would be a (nonempty) two-dimensional subvariety of $Z(f)$ (a Zariski closed set is a variety). In this case, the complement must be equal to $Z(f)$, since f is irreducible, which is impossible since U is nonempty. Hence $Z(f, \mathsf{FL}_f)$ is also two-dimensional, and thus, by the same argument just used, must be equal to $Z(f)$. Theorem 4 then implies that $Z(f)$ is ruled by (complex) lines, as claimed. $\qquad\square$

Some additional tools from algebraic geometry. The main technical tool for the analysis is the following so-called *Theorem of the Fibers*. Both Theorem 6 and Theorem 7 hold (only) for the complex field $\mathbb{C}$.

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[2]The Zariski closure of a set Y is the smallest algebraic variety V that contains Y. Y is Zariski closed if it is equal to its closure (and is therefore a variety), and is (relatively) Zariski open if its complement (within a given variety) is Zariski closed. See Cox et al. [3, Section 4.2] for further details.

Theorem 6 (Harris [12, Corollary 11.13]). *Let X be a projective variety and $\pi : X \to \mathbb{P}^d$ be a homogeneous polynomial map (i.e., the coordinate functions $x_0 \circ \pi, \ldots, x_d \circ \pi$ are homogeneous polynomials); let $Y = \pi(X)$ denote the image of X. For any $p \in Y$, let $\lambda(p) = \dim(\pi^{-1}(\{p\}))$. Then $\lambda(p)$ is an upper semi-continuous function of p in the Zariski topology on Y; that is, for any m, the locus of points $p \in Y$ such that $\lambda(p) \geq m$ is Zariski closed in Y. Moreover, if $X_0 \subset X$ is any irreducible component, $Y_0 = \pi(X_0)$ its image, and λ_0 the minimum value of $\lambda(p)$ on Y_0, then*

$$\dim(X_0) = \dim(Y_0) + \lambda_0.$$

We also need the following theorem and lemma from Harris [12].

Theorem 7 (Harris [12, Proposition 7.16]). *Let $f : X \to Y$ be the map induced by the standard projection map $\pi : \mathbb{P}^d \to \mathbb{P}^r$ (which retains r of the coordinates and discards the rest), where $r < d$, $X \subset \mathbb{P}^d$ and $Y \subset \mathbb{P}^r$ are projective varieties, X is irreducible, and Y is the image of X. Then the general fiber[3] of the map f is finite if and only if $\dim(X) = \dim(Y)$. In this case, the number of points in a general fiber of f is constant.*

In particular, when Y is two-dimensional, there exist an integer c_f and an algebraic curve $\mathcal{C}_f \subset Y$, such that for any $y \in Y \setminus \mathcal{C}_f$, we have $|f^{-1}(y)| = c_f$. With the notations of Theorem 7, the set of points $y \in Y$, such that the fiber of f over y is not equal to c_f is a Zariski closed proper subvariety of Y. For more details, we refer the reader to Shafarevich [19, Theorem II.6.4], and to Hartshorne [13, Exercise II.3.7].

Lemma 8 (Harris [12, Theorem 11.14]). *Let $\pi : X \to Y$ be a polynomial map between two projective varieties X, Y, with $Y = f(X)$ irreducible. Suppose that all the fibers $\pi^{-1}(\{p\})$ of π, for $p \in Y$, are irreducible and of the same dimension. Then X is also irreducible.*

Reguli. We rederive here the following (folklore) characterization of doubly ruled surfaces. Recall that a *regulus* is the surface spanned by all lines that meet three pairwise skew lines.[4]

Lemma 9. *Let V be an irreducible ruled surface in $\mathbb{R}^3$ or in $\mathbb{C}^3$ which is not a plane, and let $\mathcal{C} \subset V$ be an algebraic curve, such that every non-singular point $p \in V \setminus \mathcal{C}$ is incident to exactly two lines that are fully contained in V. Then V is a regulus.*

Proof. As mentioned above (see also [10]), the number of singular lines in V is finite (it is smaller than $\deg(V)^2$). For any non-singular line ℓ, fully contained in V, but not in $\mathcal{C}$, the union of lines U_ℓ intersecting ℓ and fully contained in V is a subvariety of V (see Sharir and Solomon [20, Lemma 8] for the easy proof). Each non-singular point in $\ell \setminus \mathcal{C}$ is incident to another line (other than ℓ) fully contained in V, and thus U_ℓ is the union of infinitely many lines, and is therefore two-dimensional. Since V is irreducible, it follows that $U_\ell = V$. Next, pick any triple of non-singular and non-concurrent lines ℓ_1, ℓ_2, ℓ_3 that are contained in V and intersect ℓ at distinct non-singular points of $\ell \setminus \mathcal{C}$. There has to exist such a triple, for otherwise we would have an infinite family of concurrent (or parallel)

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[3]The meaning of this statement is that the assertion holds for the fiber at any point outside some lower-dimensional exceptional subvariety.

[4]Technically, in some definitions (cf., e.g., Edge [4, Section I.22]) a regulus is a one-dimensional family of generator lines of the actual surface, i.e., a curve in the Plücker or Grassmannian space of lines, but we use here the notion of the surface spanned by these lines.

lines incident to ℓ and contained in V, and the plane that they span would then have to be contained in V, contrary to assumption. See Figure 1 for an illustration. The argument given for ℓ applies equally well to ℓ_1, ℓ_2, and ℓ_3, and implies that $U_{\ell_1} = U_{\ell_2} = U_{\ell_3} = V$. Assume that there exists some line $\tilde{\ell} \subset V$ intersecting ℓ_1 at some non-singular point p, and that $\tilde{\ell} \cap \ell_2 = \emptyset$. (We treat lines here as projective varieties, so this assumption means that $\tilde{\ell}$ and ℓ_2 are skew to one another; parallel lines are considered to be intersecting.) Since $p \in \ell_1 \subset V = U_{\ell_2}$, there exists some line $\hat{\ell}$ intersecting ℓ_2, such that $\hat{\ell} \cap \ell_1 = \{p\}$. Hence there exist three distinct lines, namely $\ell_1, \tilde{\ell}$ and $\hat{\ell}$, that are incident to p and fully contained in V. Since p is non-singular, it must be a flat point. Repeating this argument for $3\deg(V)$ non-singular points $p \in \ell_1$, it follows that ℓ_1 contains at least $3\deg(V)$ flat points, and is therefore, by the properties of flat points noted earlier, a flat line. As is easily checked, ℓ_1 can be taken to be an arbitrary non-singular line among those incident to ℓ, so it follows that every non-singular point on V is flat, and therefore, as shown in [5, 10], V is a plane, contrary to assumption.
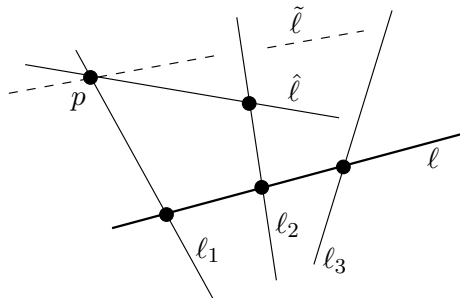

Figure 1: The structure of U_ℓ in the proof of Lemma 9.

Therefore, every non-singular line that intersects ℓ_1 at a non-singular point also intersects ℓ_2, and, similarly, it also intersects ℓ_3. This implies that the intersection of V and the surface R generated by the lines intersecting ℓ_1, ℓ_2, and ℓ_3 is two-dimensional, and is therefore equal to V, since V is irreducible. Since ℓ_1, ℓ_2 and ℓ_3 are pairwise skew, $R = V$ is a regulus, as asserted. $\qquad \square$

Real vs. complex. At this point, we would like to elaborate about the field over which the variety V is defined. Most of the basic algebraic geometry tools have been developed over the complex field $\mathbb{C}$, and some care has to be exercised when applying them over the reals. A major part of the theory developed in this paper is of this nature. For example, both Theorems 6 and 7 hold only over the complex field. As another important example, one of the main tools at our disposal is the Cayley–Salmon theorem (Theorem 4), which applies over $\mathbb{C}$. Expanding on a previously made comment, we note that even when V is a variety defined as the zero set of a real polynomial f, the vanishing of the flecnode polynomial FL_f only guarantees that the set of complex points of V is ruled by complex lines.

(A very simple example that illustrates this issue is the unit sphere σ, given by $x^2 + y^2 + z^2 = 1$, which is certainly not ruled by real lines, but the flecnode polynomial of $f(x, y, z) = x^2 + y^2 + z^2 - 1$ (trivially) vanishes on σ. This is the condition in the Cayley–Salmon theorem that guarantees that σ is ruled by (complex) lines, and indeed it does, as

is easily checked; in fact, for the same reason, every quadric is ruled by complex lines.)

This issue has not been directly addressed in Guth and Katz [11], although their theory can be adjusted to hold for the real case too, as noted later in Katz [14].

This is just one example of many similar issues that one must watch out for. It is a fairly standard practice in algebraic geometry that handles a real algebraic variety V, defined by real polynomials, by considering its complex counterpart $V_{\mathbb{C}}$, namely the set of complex points at which the defining polynomials vanish. The rich toolbox that complex algebraic geometry has developed allows one to derive various properties of $V_{\mathbb{C}}$, but some care might be needed when transporting these properties back to the real variety V, as the preceding note concerning the Cayley–Salmon theorem illustrates.

In closing this discussion, we note that most of the results developed in Section 2.2 of this paper also apply over $\mathbb{C}$, except for one crucial step, due to which we do not know how to extend Theorem 2 to the complex domain. Nevertheless, we can derive a weaker variant of it for the complex case—see a remark to that effect at the end of the paper.

Lines on a variety. In preparation for the key technical Theorem 10, given below, we make the following comments. The *Fano variety* $F(V)$ of lines fully contained in a variety V in three dimensions is parametrized by the *Plücker coordinates* of lines, as follows (see, e.g., Griffiths and Harris [8, Section 1.5]). For two points $x.y \in \mathbb{P}^3$, given in projective coordinates as $x = (x_0, x_1, x_2, x_3)$ and $y = (y_0, y_1, y_2, y_3)$, let $\ell_{x,y}$ denote the (unique) line in $\mathbb{P}^3$ incident to both x and y. The Plücker coordinates of $\ell_{x,y}$ are given in projective coordinates in $\mathbb{P}^5$ as $(\pi_{0,1}, \pi_{0,2}, \pi_{0,3}, \pi_{2,3}, \pi_{3,1}, \pi_{1,2})$, where $\pi_{i,j} = x_i y_j - x_j y_i$. Under this parametrization, the set of lines in $\mathbb{P}^3$ corresponds bijectively to the set of points in $\mathbb{P}^5$ lying on the *Klein quadric* given by the quadratic equation $\pi_{0,1}\pi_{2,3} + \pi_{0,2}\pi_{3,1} + \pi_{0,3}\pi_{1,2} = 0$ (which is always satisfied by the Plücker coordinates of a line). Given a surface V in $\mathbb{P}^3$, the set of lines fully contained in V, represented by their Plücker coordinates in $\mathbb{P}^5$, is a subvariety of the Klein quadric, which, as above, is denoted by $F(V)$, and is called the *Fano variety* of V; see Harris [12, Lecture 6, page 63] for details, and [12, Example 6.19] for an illustration, and for a proof that $F(V)$ is indeed a variety. The Plücker coordinates are continuous in the sense that if one takes two points ℓ, ℓ' on the Klein quadric that are near each other, the lines in $\mathbb{P}^3$ that they correspond to are also near to one another, in an obvious sense whose precise details are omitted here.

Given a plane π by a homogeneous equation $A_0 x_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 = 0$, and a line ℓ not fully contained in π, given in Plücker coordinates as $(\pi_{0,1}, \pi_{0,2}, \pi_{0,3}, \pi_{2,3}, \pi_{3,1}, \pi_{1,2})$, their point of intersection is given in homogeneous coordinates by $(A \cdot m, A \times m - A_0 d)$, where $d = (\pi_{0,1}, \pi_{0,2}, \pi_{0,3})$, $m = (\pi_{2,3}, \pi_{3,1}, \pi_{1,2})$, and where $\cdot$ stands for the scalar product, and $\times$ for the vector product. This, together with the continuity argument stated above, implies that, if the Fano variety $F(V)$ is one-dimensional, and ℓ is a line represented by a regular point of $F(V)$, then the cross section of the union of the lines that lie near ℓ in $F(V)$ with a generic plane π is a simple arc. When ℓ is a singular point of $F(V)$, then the cross section of the union of the lines that lie near ℓ in $F(V)$ with a generic plane π is a union of simple arcs meeting at $\ell \cap \pi$ where some of these arcs might appear with multiplicity; the number of these arcs is determined by the multiplicity of the singularity of ℓ.

Singly ruled surfaces. The following result is another folklore result in the theory of ruled surfaces, used in many studies (such as Guth and Katz [11]). We give a detailed and rigorous proof, to make our presentation as self-contained as possible; we are not aware of any similarly detailed argument in the literature.

Theorem 10. *(a) Let V be an irreducible ruled two-dimensional surface of degree $D > 1$ in $\mathbb{R}^3$ (or in $\mathbb{C}^3$), which is not a regulus. Then, except for at most two exceptional lines, the lines that are fully contained in V are parametrized by an irreducible algebraic curve Σ_0 in the Plücker space $\mathbb{P}^5$, and thus yield a 1-parameter family of generator lines $\ell(t)$, for $t \in \Sigma_0$, that depend continuously on the real or complex parameter t. Moreover, if $t_1 \neq t_2$, and $\ell(t_1) \neq \ell(t_2)$, then there exist sufficiently small and disjoint neighborhoods Δ_1 of t_1 and Δ_2 of t_2, such that all the lines $\ell(t)$, for $t \in \Delta_1 \cup \Delta_2$, are distinct.*

(b) There exists a one-dimensional curve $\mathcal{C} \subset V$, such that any point p in $V \setminus \mathcal{C}$ is incident to exactly one generator line of V.

Remark. For a detailed description of the algebraic representation of V by generators, as in part (a) of the lemma, see Edge [4, Section II].

Proof. Assume first that we are working over $\mathbb{C}$. Consider the Fano variety $F(V)$ of V, as defined above. We claim that all the irreducible components of $F(V)$ are at most one-dimensional. Informally, if any component Σ_0 of $F(V)$ were two-dimensional, then the set $\{(p, \ell) \in V \times F(V) \mid p \in \ell\}$ would be three-dimensional, so, "on average", the set of lines of $F(V)$ incident to a point $p \in V$ would be one-dimensional, implying that most points of V are incident to infinitely many lines that are fully contained in V, which can happen only when V is a plane (or a non-planar cone, which cannot arise with a non-singular point p as an apex), contrary to assumption.

To make this argument formal, consider the set (already mentioned above)

$$W := \{(p, \ell) \mid p \in \ell, \ell \in F(V)\} \subset V \times F(V),$$

and the two projections

$$\Psi_1 : W \to V, \quad \Psi_2 : W \to F(V)$$

to the first and second factors of the product $V \times F(V)$.

W can formally be defined as the zero set of suitable homogeneous polynomials; briefly, with an appropriate parameterization of lines in $\mathbb{P}^3$ and the use of homogeneous coordinates, the condition $p \in \ell$ can be expressed as the vanishing of two suitable homogeneous polynomials, and the other defining polynomials are those that define the projective variety $F(V)$. Therefore, W is a projective variety.

Consider an irreducible component Σ_0 of $F(V)$ (which is also a projective variety); put

$$W_0 := \Psi_2^{-1}(\Sigma_0) = \{(p, \ell) \in W \mid \ell \in \Sigma_0\}.$$

Since W and Σ_0 are projective varieties, so is W_0. As is easily verified, $\Psi_2(W_0) = \Sigma_0$ (that is, Ψ_2 is surjective). We claim that W_0 is irreducible. Indeed, for any $\ell \in \Sigma_0$, the fiber of the map $\Psi_2|_{W_0} : W_0 \to \Sigma_0$ over ℓ is $\{(p, \ell) \mid p \in \ell\}$ which is (isomorphic to) a line, and is therefore irreducible of dimension one. As Σ_0 is irreducible, Lemma 8 implies that W_0 is also irreducible, as claimed.

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For a point $p \in \Psi_1(W_0)$, consider the set $\Sigma_{0,p} = \Psi_1|_{W_0}^{-1}(\{p\})$, put $\lambda(p) = \dim(\Sigma_{0,p})$, and let $\lambda_0 := \min_{p \in \Psi_1(W_0)} \lambda(p)$. By the Theorem of the Fibers (Theorem 6), applied to the map $\Psi_1|_{W_0} : W_0 \to V$, we have

$$\dim(W_0) = \dim(\Psi_1(W_0)) + \lambda_0. \tag{3}$$

We claim that $\lambda_0 = 0$. In fact, $\lambda(p) = 0$ for all points $p \in V$, except for at most one point. Indeed, if $\lambda(p) \geq 1$ for some point $p \in V$, then $\Sigma_{0,p}$ is (at least) one-dimensional, and V, being irreducible, is thus a cone with apex at p; since V can have at most one apex, the claim follows. Hence $\lambda_0 = 0$, and therefore

$$\dim(W_0) = \dim(\Psi_1(W_0)) \leq \dim(V) = 2. \tag{4}$$

Next, assume, for a contradiction, that $\dim(\Sigma_0) = 2$. For a point (i.e., a line in $\mathbb{P}^3$) $\ell \in \Psi_2(W_0)$, the set $\Psi_2|_{W_0}^{-1}(\{\ell\}) = \{(p, \ell) \mid p \in \ell\}$ is one-dimensional (the equality follow from the way W_0 is defined). Conforming to the notations in the Theorem of the Fibers, we have $\mu(\ell) := \dim\left(\Psi_2|_{W_0}^{-1}(\{\ell\})\right) = 1$, and thus $\mu_0 := \min_{\ell \in \Psi_2(W_0)} \mu(\ell) = 1$. Also, by assumption, $\dim(\Psi_2(W_0)) = \dim(\Sigma_0) = 2$. By the Theorem of the Fibers, applied this time to $\Psi_2|_{W_0} : W_0 \to \Sigma_0$, we thus have

$$\dim(W_0) = \dim(\Psi_2(W_0)) + \mu_0 = 3, \tag{5}$$

contradicting Equation (4). Therefore, every irreducible component of $F(V)$ is at most one-dimensional, as claimed.

Let Σ_0 be such an irreducible component, and let $W_0 := \Psi_2^{-1}(\Sigma_0)$, as above. As argued, for every $p \in V$, the fiber of $\Psi_1|_{W_0}$ over p is non-empty and finite, except for at most one point p (the apex of V if V is a cone). Since W_0 is irreducible, Theorem 7 implies that there exists a Zariski open set $\mathcal{O} \subseteq V$, such that for any point $p \in \mathcal{O}$, the fiber of $\Psi_1|_{W_0}$ over p has fixed cardinality c_f. Put $\mathcal{C} := V \setminus \mathcal{O}$. Being the complement of a Zariski open subset of the two-dimensional irreducible variety V, $\mathcal{C}$ is (at most) a one-dimensional variety. If $c_f \geq 2$, then, by Lemma 9, V is a regulus. Otherwise, $c_f = 1$ (c_f cannot be zero for a ruled surface), meaning that, for every $p \in V \setminus \mathcal{C}$, there is exactly one line ℓ, such that $(p, \ell) \in W_0$, i.e., Σ_0 contains exactly one line incident to p and contained in V.

Moreover, we observe that the union of lines of Σ_0 is the entire variety V. Indeed, by Equation (3), it follows that $\dim(W_0) = \dim(\Psi_1(W_0))$. By Equations (4) and (5), without the contrary assumption that $\dim(\Sigma_0) = 2$, it follows that $\dim(W_0) = 2$, and therefore $\dim(\Psi_1(W_0)) = 2$. That is, the variety $\Psi_1(W_0)$, which is the union of the lines of Σ_0, must be the entire variety V, because it is two-dimensional and is contained in the irreducible variety V.

To recap, we have proved that if Σ_0 is a one-dimensional component of $F(V)$, then the union of lines that belong to Σ_0 covers V, and that there exists a one-dimensional subvariety (a curve) $\mathcal{C} \subset V$ such that, for every $p \in V \setminus \mathcal{C}$, Σ_0 contains exactly one line incident to p and contained in V.

Since V is a ruled surface, some component of $F(V)$ has to be one-dimensional, for otherwise we would only have a finite number of lines fully contained in V. We claim that there is exactly one irreducible component of $F(V)$ which is one-dimensional. Indeed, assume to the contrary that Σ_0, Σ_1 are two (distinct) one-dimensional irreducible components

of $F(V)$. As we observed, the union of lines parameterized by Σ_0 (resp., Σ_1) covers V. Let $\mathcal{C}_0, \mathcal{C}_1 \subset V$ denote the respective excluded curves, so that, for every $p \in V \setminus \mathcal{C}_0$ (resp., $p \in V \setminus \mathcal{C}_1$) there exists exactly one line in Σ_0 (resp., Σ_1) that is incident to p and contained in V.

Next, notice that the intersection $\Sigma_0 \cap \Sigma_1$ is a subvariety strictly contained in the irreducible one-dimensional variety Σ_0 (since Σ_0 and Σ_1 are two distinct irreducible components of $F(V)$), so it must be zero-dimensional, and thus finite. Let $\mathcal{C}_{01}$ denote the union of the finitely many lines in $\Sigma_0 \cap \Sigma_1$, and put $\mathcal{C} := \mathcal{C}_0 \cup \mathcal{C}_1 \cup \mathcal{C}_{01}$. For any point $p \in V \setminus \mathcal{C}$, there are two (distinct) lines incident to p and fully contained in V (one belongs to $\Sigma_{0,p}$ and the other to $\Sigma_{1,p}$). Lemma 9 (with $\mathcal{C}$ as defined above) then implies that V is a regulus, contrary to assumption.

In other words, the unique one-dimensional irreducible component Σ_0 of $F(V)$ serves as the desired 1-parameter family of generators for V. (The local parameterization of Σ_0 can be obtained, e.g., by using a suitable Plücker coordinate of its lines.) In addition to Σ_0, there is a finite number of zero-dimensional components (i.e., points) of $F(V)$. They correspond to a finite number of lines, fully contained in V, and not parametrized by Σ_0. Since the union of the lines in Σ_0 covers V, any of these additional lines ℓ is *exceptional*, in the sense that each point on ℓ is also incident to a generator (different from ℓ). By Guth and Katz [11, Corollary 3.6], there are at most two such exceptional lines, so there are at most two zero-dimensional components of $F(V)$. For the sake of completeness, we sketch a proof of our own of this fact; see Lemma 18 in the appendix.

This establishes part (a) of the lemma, when V is defined over $\mathbb{C}$.

If V is defined over $\mathbb{R}$, we proceed as above, i.e., consider instead the complex variety $V_\mathbb{C}$ corresponding to V. As we have just proven, the unique one-dimensional irreducible component Σ_0 of $F(V)$ (regarded as a complex variety) is a (complex) 1-parameter family of generators for the set of complex points of V. Since V is real, the (real) Fano variety of V consists of the real points of $F(V)$, i.e., it is $F(V) \cap \mathbb{P}^5(\mathbb{R})$. As we have argued, the (complex) $F(V)$ is the union of Σ_0 with at most two other points. If $\Sigma|_\mathbb{R} := \Sigma_0 \cap \mathbb{P}^5(\mathbb{R})$ were zero-dimensional, the real $F(V)$ would also be discrete, so V would fully contain only finitely many (real) lines, contradicting the assumption that V is ruled by real lines. Therefore, $\Sigma_0|_\mathbb{R}$ is a one-dimensional irreducible component of the real Fano variety of V. (It is irreducible, since otherwise the complex Σ_0 would be reducible too, as is easily checked.)

Summarizing, we have shown that there exists exactly one irreducible one-dimensional component Σ_0 of $F(V)$, and a corresponding one-dimensional subvariety $\mathcal{C} \subset V$, such that, for each point $p \in V \setminus \mathcal{C}$, Σ_0 contains exactly one line that is incident to p (and contained in V). In addition to Σ_0, $F(V)$ might also contain up to two zero-dimensional (i.e., singleton) components, whose elements are the exceptional lines mentioned above. Let $\mathcal{D}$ denote the union of $\mathcal{C}$ and of the at most two exceptional lines; $\mathcal{D}$ is clearly a one-dimensional subvariety of V. Then, for any point $p \in V \setminus \mathcal{D}$, there is exactly one line incident to p and fully contained in V, as claimed. This establishes part (b), and thus completes the proof of the lemma. $\qquad\square$

To complete the picture, we bridge between the "conservative" and the "liberal" definitions of a ruled surface.

Lemma 11. *Let V be a two-dimensional irreducible surface for which there exists a Zariski open subset $\mathcal{O} \subseteq V$ with the property that each point $p \in \mathcal{O}$ is incident to a line that is fully*

contained in V. Then this property holds for every point of V.

Proof. Consider the variety $W = \{(p, \ell) \mid p \in \ell, \ell \in F(V)\}$ used in the proof of Theorem 15. The projection $\Psi_1(W)$, in the notation of the preceding proof, is a variety (assuming that we work in the complex projective setting) contained in V. By assumption, it contains the Zariski open (and hence dense) subset $\mathcal{O}$, so, being a variety (i.e., Zariski closed), it is the entire V, as claimed. □

Ruled surfaces that are neither planes nor reguli, are called *singly ruled* surfaces (a terminology justified by Theorem 10). As in the proof of Theorem 10), a line ℓ, fully contained in an irreducible singly ruled surface V, such that ℓ contains infinitely many points, each incident to another line fully contained in V, is called an *exceptional* line of V. If there exists a point $p_V \in V$, which is incident to infinitely many lines fully contained in V, then p_V is called an *exceptional* point of V. By Guth and Katz [11], V can contain at most one exceptional point p_V (in which case V is a cone with p_V as its apex), and at most two exceptional lines, as already noted. (This argument can be shown to hold over both $\mathbb{R}$ and $\mathbb{C}$.)

2.2 The proof

For a point p on an irreducible singly ruled surface V, which is not the exceptional point of V, we let $\Lambda_V(p)$ denote the number of generator lines passing through p and fully contained in V (so if p is incident to an exceptional line, we do not count that line in $\Lambda_V(p)$). We also put $\Lambda_V^*(p) := \max\{0, \Lambda_V(p) - 1\}$. Finally, if V is a cone and p_V is its exceptional point (that is, apex), we put $\Lambda_V(p_V) = \Lambda_V^*(p_V) := 0$. We also consider a variant of this notation, where we are also given a finite set L of lines (where not all lines of L are necessarily contained in V), which does not contain any of the (at most two) exceptional lines of V. For a point $p \in V$, we let $\lambda_V(p; L)$ denote the number of lines in L that pass through p and are fully contained in V, with the same provisions as above, namely that we do not count incidences with exceptional lines, nor do we cound incidences with an exceptional point, and put $\lambda_V^*(p; L) := \max\{0, \lambda_V(p; L) - 1\}$. If V is a cone with apex p_V, we put $\lambda_V(p_V; L) = \lambda_V^*(p_V; L) = 0$. We clearly have $\lambda_V(p; L) \leq \Lambda_V(p)$ and $\lambda_V^*(p; L) \leq \Lambda_V^*(p)$, for each point p.

Lemma 12. *Let V be an irreducible singly ruled two-dimensional surface of degree $D > 1$ in $\mathbb{R}^3$ or in $\mathbb{C}^3$. Then, for any line ℓ, except for the (at most) two exceptional lines of V, we have*

$$\sum_{p \in \ell \cap V} \Lambda_V(p) \leq D \qquad \text{if } \ell \text{ is not fully contained in } V,$$

$$\sum_{p \in \ell \cap V} \Lambda_V^*(p) \leq D \qquad \text{if } \ell \text{ is fully contained in } V.$$

Proof. We note that the difference between the two cases arises because we do not want to count ℓ itself—the former sum would be infinite when ℓ is fully contained in V. Note also that if V is a cone and $p_V \in \ell$, we ignore in the sum the infinitely many lines incident to p_V and contained in V.

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The proof is a variant of an observation due to Salmon [18] and repeated in Guth and Katz [11] over the real numbers, and later in Kollár [15] over general fields.

By Theorem 10(a), excluding the exceptional lines of V, the set of lines fully contained in V can be parameterized as a (real or complex) 1-parameter family of generator lines $\ell(t)$, represented by the irreducible curve $\Sigma_0 \subseteq F(V)$. Let $V^{(2)}$ denote the locus of points of V that are incident to at least two generator lines fully contained in V. By Theorem 10(b), $V^{(2)}$ is contained in some one-dimensional curve $\mathcal{C}$.

Let $p \in V \cap \ell$ be a point incident to k generator lines of V, other than ℓ, for some $k \geq 1$. In case V is a cone, we assume that $p \neq p_V$. Denote the generator lines incident to p (other than ℓ, if $\ell \subset V$, in which case it is assumed to be a generator) as $\ell_i = \ell(t_i)$, for $t_i \in \Sigma_0$ and for $i = 1, \ldots, k$. (If ℓ_i is a singular point of $F(V)$, it may arise as $\ell(t_i)$ for several values of t_i, and we pick one arbitrary such value.) Let π be a generic plane containing ℓ, and consider the curve $\gamma_0 = V \cap \pi$, which is a plane curve of degree D. Since $V^{(2)} \subseteq \mathcal{C}$ is one-dimensional, a generic choice of π will ensure that $V^{(2)} \cap \pi$ is a discrete set (since ℓ is non-exceptional, it too meets $V^{(2)}$ in a discrete set).

There are two cases to consider: If ℓ is fully contained in V (and is thus a generator), then γ_0 contains ℓ. In this case, let γ denote $\gamma_0 \setminus \ell$; it is also a plane algebraic curve, of degree at most $D - 1$. Otherwise, we put $\gamma := \gamma_0$. By Theorem 10(a), we can take, for each $i = 1, \ldots, k$, a sufficiently small open (real or complex) neighborhood Δ_i along Σ_0 containing t_i, so that, for any $1 \leq i < j \leq k$, all the lines $\ell(t)$, for $t \in \Delta_i \cup \Delta_j$, are distinct. Put $V_i := \bigcup_{t \in \Delta_i} \ell(t)$. Recall that $V_i \cap \pi_i$ is either a simple arc or a union of simple arcs meeting at p (depending on whether or not ℓ_i is a regular point of Σ_0); in the latter case, take γ_i to be any one of these arcs. Each of the arcs γ_i passes through p and is contained in γ. Moreover, since π is generic, the arcs γ_i are all distinct. Indeed, for any $i \neq j$, and any point $q \in \gamma_i \cap \gamma_j$, there exist $t_i \in \Delta_i, t_j \in \Delta_j$ such that $\ell(t_i) \cap \pi = \ell(t_j) \cap \pi = q$, and $\ell(t_i) \neq \ell(t_j)$ (by the properties of these neighborhoods). Therefore, any point in $\gamma_i \cap \gamma_j$ is incident to (at least) two distinct generator lines fully contained in V. Again, the generic choice of π ensures that $\gamma_i \cap \gamma_j \subseteq V^{(2)}$ is a discrete set, so, in particular, γ_i and γ_j are distinct.

We have therefore shown that (i) if ℓ is not contained in V then p is a singular point of γ of multiplicity at least k (for $k \geq 2$; when $k = 1$ the point does not have to be singular), and (ii) if ℓ is contained in V then p is singular of multiplicity at least $k + 1$. We have $k \geq \Lambda_V(p)$ (resp., $k \geq \Lambda_V^*(p)$) if ℓ is not fully contained (resp., is fully contained) in V. (We may have an inequality if V is a cone and p is its apex, since we then do not count in $\Lambda_V(p)$ or in $\Lambda_V^*(p)$ the lines that pass through p.) As argued at the beginning of Section 2.1, the line ℓ can intersect γ in at most D points, *counted with multiplicity*, and the result follows. $\square$

We also need the following result, established by Guth and Katz [10]; see also [5]. It is an immediate consequence of the Cayley–Salmon theorem (Theorem 4) and a suitable extension of Bézout's theorem for intersecting surfaces (see Fulton [7, Proposition 2.3]).

Proposition 13 (Guth and Katz [11])**.** *Let V be an irreducible two-dimensional variety in $\mathbb{C}^3$ of degree D. If V fully contains more than $11D^2 - 24D$ lines then V is ruled by (possibly complex) lines.*

Corollary 14. *Let V be an irreducible two-dimensional variety in $\mathbb{R}^3$ or $\mathbb{C}^3$ of degree D that does not contain any planes. Then the number of lines that are fully contained in the union of the non-ruled components of V is $O(D^2)$.*

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Proof. Let $V_1, \ldots, V_k$ denote those irreducible components of V that are not ruled by lines. By Proposition 13, for each i, the number of lines fully contained in V_i is at most $11\deg(V_i)^2 - 24\deg(V_i)$. Summing over $i = 1, \ldots, k$, the number of lines fully contained in the union of the non-ruled components of V is at most $\sum_{i=1}^{k} 11\deg(V_i)^2 = O(D^2)$. $\qquad\square$

The following theorem, which we believe to be of independent interest in itself, is the main technical ingredient of our analysis.

Theorem 15. *Let V be a possibly reducible two-dimensional algebraic surface of degree $D > 1$ in $\mathbb{R}^3$ or in $\mathbb{C}^3$, with no linear components. Let P be a set of m distinct points on V and let L be a set of n distinct lines fully contained in V. Then there exists a subset $L_0 \subseteq L$ of at most $O(D^2)$ lines, such that the number of incidences between P and $L \setminus L_0$ satisfies*

$$I(P, L \setminus L_0) = O\left(m^{1/2}n^{1/2}D^{1/2} + m + n\right). \tag{6}$$

Proof. Consider the irreducible components $W_1, \ldots, W_k$ of V. By Corollary 14, the number of lines contained in the union of the non-ruled components of V is $O(D^2)$, and we place all these lines in the exceptional set L_0. In what follows we thus consider only ruled components of V. For simplicity, continue to denote them as $W_1, \ldots, W_k$, and note that $k \leq D/2$.

We further augment L_0 as follows. We first dispose of lines of L that are fully contained in more than one ruled component W_i. We claim that their number is $O(D^2)$. Indeed, for any pair W_i, W_j of distinct components, the intersection $W_i \cap W_j$ is a curve of degree $\deg(W_i)\deg(W_j)$, which can therefore contain at most $\deg(W_i)\deg(W_j)$ lines (by the generalized version of Bézout's theorem [7, Proposition 2.3], already mentioned in connection with Proposition 13). Since $\sum_{i=1}^{k} \deg(W_i) \leq D$, we have

$$\sum_{i \neq j} \deg(W_i)\deg(W_j) \leq \left(\sum_i \deg(W_i)\right)^2 = O(D^2),$$

as claimed. We add to L_0 all the $O(D^2)$ lines in L that are contained in more than one ruled component, and all the exceptional lines of all singly ruled components. The number of lines of the latter kind is at most $2k \leq 2 \cdot (D/2) = D$, so the size of $|L_0|$ is still $O(D^2)$. Hence, each line of $L_1 := L \setminus L_0$ is fully contained in a unique ruled component of V, and is a generator of that component.

The strategy of the proof is to consider each line ℓ of L_1, and to estimate the number of its incidences with the points of P in an indirect manner, via Lemma 12, applied to ℓ and to each of the ruled components W_j of V. We recall that ℓ is fully contained in a unique component W_i, and treat that component in a somewhat different manner than the treatment of the other components.

In more detail, we proceed as follows. We first ignore, for each singly ruled *conic* component W_i, the incidences between its apex (exceptional point) p_{W_i} and the lines of L_1 that are contained in W_i. We refer to these incidences as *conical incidences* and to the other incidences as *non-conical*. When we talk about a line ℓ incident to another line ℓ' at a point p, we will say that ℓ is *conically incident* to ℓ' (at p) if p is the apex of some conic component W_i and ℓ' is fully contained in W_i (and thus incident to p). In all other cases, we will say that ℓ is *non-conically incident* to ℓ' (at p). (Note that this definition is asymmetric in ℓ and ℓ'; in particular, ℓ does not have to lie in the cone W_i.) We note that the number

of conical point-line incidences is at most n, because each line of L_1 is fully contained in a unique component W_i, so it can be involved in at most one conical incidence (at the apex of W_i, when W_i is a cone).

We next prune away points $p \in P$ that are non-conically incident to at most three lines of L_1. (Note that p might be an apex of some conic component(s) of V; in this case p is removed if it is incident to at most three lines of L_1 that are not contained in any of these components.) We lose $O(m)$ (non-conical) incidences in this process. Let P_1 denote the subset of the remaining points.

Claim. Each line $\ell \in L_1$ is non-conically incident, at points of P_1, to at most $4D$ other lines of L_1.

Proof. Fix a line $\ell \in L_1$ and let W_i denote the unique ruled component that fully contains ℓ. Let W_j be any of the other ruled components. We estimate the number of lines of L_1 that are non-conically incident to ℓ and are fully contained in W_j.

If W_j is a regulus, there are at most four such lines, since ℓ meets the quadratic surface W_j in at most two points, each incident to exactly two generators (and to no other lines contained in W_j). Assume then that W_j is singly ruled. By Lemma 12, we have

$$\sum_{p \in \ell \cap W_j} \lambda_{W_j}(p; L_1) \le \sum_{p \in \ell \cap W_j} \Lambda_{W_j}(p) \le \deg(W_j).$$

Note that, by definition, the above sum counts only non-conical incidences (and only with generators of W_j, but the exceptional lines of W_j have been removed from L_1 anyway). For W_j a regulus, we write the bound 4 as $\deg(W_j) + 2$.

We sum this bound over all components $W_j \ne W_i$, including the reguli. Denoting the number of reguli by ρ, which is at most $D/2$, we obtain a total of

$$\sum_{j \ne i} \deg(W_j) + 2\rho \le D + 2\rho \le 2D.$$

Consider next the component W_i containing ℓ. Assume first that W_i is a regulus. Each point $p \in P_1 \cap \ell$ can be incident to at most one other line of L_1 contained in W_i (the other generator of W_i through p). Since p is in P_1, it is non-conically incident to at least $3 - 2 = 1$ other line of L_1, contained in some other ruled component of V. That is, the number of lines that are (non-conically) incident to ℓ and are contained in W_i, which apriorily can be arbitrarily large, is nevertheless at most the number of other lines (not contained in W_i) that are non-conically incident to ℓ, which, as shown above, is at most $2D$.

If W_i is not a regulus, Lemma 12 implies that

$$\sum_{p \in \ell \cap W_i} \Lambda^*_{W_i}(p) \le \deg(W_i) \le D,$$

where again only non-conical incidences are counted in this sum (and only with generators). That is, the number of lines of L_1 that are non-conically incident to ℓ (at points of P_1) and are contained in W_i is at most D. Adding the bound for W_i, which has just been shown to be either D or $2D$, to the bound $2D$ for the other components, the claim follows. $\square$

To proceed, choose a threshold parameter $\xi \ge 3$, to be determined shortly. Each point $p \in P_1$ that is non-conically incident to at most ξ lines of L contributes at most ξ (non-conical) incidences, for a total of at most $m\xi$ incidences. (Recall that the overall number

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of conical incidences is at most n.) For the remaining incidences, let ℓ be a line in L_1 that is incident to t points of P_1, so that each such point p is non-conically incident to at least $\xi + 1$ lines of L_1 (one of which is ℓ). By the preceding claim, we have $t \leq 4D/\xi$; summing this over all $\ell \in L_1$, we obtain a total of at most $4nD/\xi$ incidences. We can now bring back the removed points of $P \setminus P_1$, since the non-conical incidences that they are involved in are counted in the bound $m\xi$. That is, we have

$$I(P, L_1) \leq m\xi + n + \frac{4nD}{\xi}.$$

We now choose $\xi = (nD/m)^{1/2}$. For this choice to make sense, we want to have $\xi \geq 3$, which will be the case if $9m \leq nD$. In this case we get the bound $O\left(m^{1/2}n^{1/2}D^{1/2} + n\right)$. If $9m > nD$ we take $\xi = 3$ and obtain the bound $O(m)$. Combining these bounds, the lemma follows. $\qquad\square$

The final stretch. It remains to bound the number $I(P, L_0)$ of incidences involving the lines in L_0. We have $|L_0| = O(D^2)$; actually, $|L_0| = \min\{n, O(D^2)\}$. We estimate $I(P, L_0)$ using Guth and Katz's bound ([11]; see Theorem 1), recalling that no plane contains more than s lines of L_0. We thus obtain

$$I(P, L_0) = O\left(m^{1/2}|L_0|^{3/4} + m^{2/3}|L_0|^{1/3}s^{1/3} + m + |L_0|\right) \tag{7}$$
$$= O\left(m^{1/2}n^{1/2}D^{1/2} + m^{2/3}\min\{n, D^2\}^{1/3}s^{1/3} + m + n\right).$$

Combining the bounds in (6) and in (7) yields the asserted bound on $I(P, L)$.

Reduction to three dimensions. To complete the analysis, we need to consider the case where V is a two-dimensional variety embedded in $\mathbb{R}^d$, for $d > 3$.

Let H be a generic 3-flat, and denote by P^*, L^*, and V^* the respective projections of P, L, and V onto H. Since H is generic, we may assume that all the projected points in P^* are distinct, and so are all the projected lines in L^*. Clearly, every incidence between a point of P and a line of L corresponds to an incidence between the projected point and line. Since no 2-flat contains more than s lines of L, and H is generic, repeated applications of Theorem 17 in the Appendix imply that no plane in H contains more than s lines of L^*.

One subtle point is that the set-theoretic projection V^* of V does not have to be a real algebraic variety (it is only a semi-algebraic set), but it is always contained in a two-dimensional real algebraic variety $\tilde{V}$, which we call, as we did in an earlier work [21], the *algebraic projection* of V; it is the zero set of all polynomials belonging to the ideal of polynomials vanishing on V, after eliminating variables in the complementary space of H (this is also known as an *elimination ideal* of V; see Cox et al. [3] for details). We can also think of $\tilde{V}$ as the Zariski closure of V^*. Since the closure of a projection does not increase the original degree (see, e.g., Harris [12]), $\deg(\tilde{V}) \leq D$. That $\tilde{V}$ does not contain a 2-flat follows by a suitable adaptation of the argument in Sharir and Solomon [21, Lemma 2.1] (which is stated there for $d = 4$ over the reals), that applies for general d and over the complex field too.

In conclusion, we have $I(P, L) \leq I(P^*, L^*)$, where P^* is a set of m points and L^* is a set of n lines, all contained in the two-dimensional algebraic variety $\tilde{V}$, which is of degree

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at most D and does not contain any plane, and no plane contains more than s lines of L^*. The preceding analysis thus implies that the bound asserted in the theorem applies in any dimension $d \geq 3$. $\qquad\square$

3   Discussion

(1) We note that most of the proof of Theorem 2 can be carried out over the complex domain. The only place where we (implicitly) use the fact that the underlying field is $\mathbb{R}$ is in the final step, where we apply the bound of Guth and Katz, as a "black box", to $I(P, L_0)$. If we skip this step, we remain with the weaker, albeit still useful, Theorem 15, which holds over $\mathbb{C}$ too. This is the part of our analysis that we apply in our companion work [22] on point-line incidences in four dimensions.

(2) As mentioned in the introduction, Corollary 3 can be extended to the case where V, which is of constant degree D, also contains planes. Here too, we assume that no plane contains more than s lines of L, but this time it is not necessarily the case that $s \leq D$.

Let $\pi_1, \ldots, \pi_k$ denote the planar components of V, where $k \leq D = O(1)$. For each $i = 1, \ldots, k$, the number of incidences within π_i, namely, between the set P_i of points contained in π_i and the set L_i of lines fully contained in π_i, is

$$I(P_i, L_i) = O\left(|P_i|^{2/3}|L_i|^{2/3} + |P_i| + |L_i|\right) = O\left(m^{2/3}s^{2/3} + m + s\right).$$

Summing these bounds over the $k = O(1)$ planes, we get the same asymptotic bound for the overall number of the incidences within these planes. Any other incidence between a point p lying in one of these planes π_i and a line ℓ not contained in π_i can be uniquely identified with the intersection of ℓ with π_i. The overall number of such intersections is at most $nk = O(n)$. This leads to the following extension of Corollary 3.

Corollary 16. *Let P be a set of m distinct points and L a set of n distinct lines in $\mathbb{R}^d$, and let $s \leq n$ be a parameter, such that all the points and lines lie in a common algebraic surface of constant degree, and no 2-flat contains more than s lines of L. Then*

$$I(P, L) = O\left(m^{2/3}s^{2/3} + m + n\right),$$

where the constant of proportionality depends on the degree of the surface.

(3) To us, one of the significant achievements of the analysis in this paper is that our bound does not include the term $O(nD)$. Such a term arises, as in the preceding remark, when one considers incidences between points lying in some irreducible component of V and lines not contained in that component. These incidences can be bounded by nD, by charging them, as above, to line-component intersections. This term also arises naturally in the analysis of Guth and Katz [11] when considering incidences involving lines not fully contained in the zero set of the partitioning polynomial that is used in their analysis. When D is large (say, $D = O(n^{1/2})$), the term nD is too large when compared with the bound of [11], but the term $m^{1/2}n^{1/2}D^{1/2}$ is fine.

(4) Another issue that arises in our analysis is that, in the final step of the proof, we bound the number of incidences involving lines of L_0 using the Guth–Katz bound. It would be

interesting, aesthetically speaking, to replace this step by a different, simpler, and more direct derivation. A more profound challenge would be to make this part work also over $\mathbb{C}$, so that our bound would hold over the complex field too.

(5) Concerning lower bounds, we do not know whether our result is tight. A specific subproblem here is to bound the number of incidences within a singly ruled irreducible surface (in three dimensions, say). The analysis in Guth and Katz [11] yields the bound $O(m + nD)$, which (see item (3) above) is in general too weak.

(6) Finally, an interesting challenge is to establish a similar bound for $I(P, L)$, for the case where the points of P lie on a two-dimensional variety V, but the lines need not be contained in V.

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A   Some proofs

Generic projections preserve non-planarity.

Theorem 17. *Let ℓ_1, ℓ_2, ℓ_3 be three non-coplanar lines in $\mathbb{R}^d$. Then, under a generic projection of $\mathbb{R}^d$ onto some hyperplane H, the respective images $\ell_1^*, \ell_2^*, \ell_3^*$ of these lines are still non-coplanar.*

Proof. Assume without loss of generality that the (generic) hyperplane H onto which we project passes through $(0, 0, 0, 0) \in \mathbb{R}^d$, and let w denote the unit vector normal to H. The projection $h : \mathbb{R}^d \mapsto H$ is then given by $h(v) = v - (v \cdot w)w$.

Assume first that two of the three given lines, say ℓ_1, ℓ_2, are skew (i.e., not coplanar). Let $\tilde{\ell}_1, \tilde{\ell}_2$ denote their projection onto H. If $\tilde{\ell}_1, \tilde{\ell}_2$ are coplanar they are either intersecting or parallel. If they are intersecting, then there are points $p_1 \in \ell_1, p_2 \in \ell_2$ that project to the same point, i.e., $p_1 - p_2$ has the same direction as w. Then w belongs to the set $\{\frac{p_1 - p_2}{\|p_1 - p_2\|} \mid p_1 \in \ell_1, p_2 \in \ell_2\}$. Since this is a two-dimensional set, it will be avoided for a generic choice of w, which is a generic point in $\mathbb{S}^{d-1}$, a set that is at least three-dimensional.

If $\tilde{\ell}_1, \tilde{\ell}_2$ are parallel, let v_1, v_2 denote the directions of ℓ_1, ℓ_2. Since $v_1 - (v_1 \cdot w)w$ and $v_2 - (v_2 \cdot w)w$ are vectors in the directions of $\tilde{\ell}_1, \tilde{\ell}_2$, and are thus parallel, it follows that w must be a linear combination of v_1 and v_2. Since $\|w\| = 1$, the resulting set of possible directions is only one-dimensional, and, again, it will be avoided with a generic choice of w.

We may therefore assume that every pair of lines among ℓ_1, ℓ_2, ℓ_3 are coplanar. Since these three lines are not all coplanar, the only two possibilities are that either they are all mutually parallel, or all concurrent.

Assume first that they are concurrent, say they all pass through the origin. Their projections are in the directions $v_i - (v_i \cdot w)w$, for $i = 1, 2, 3$. If these projections are coplanar then there exist coefficients $\alpha_1, \alpha_2, \alpha_3$, not all zero, such that $\sum_i \alpha_i(v_i - (v_i \cdot w)w) = 0$. That is, putting $u := \sum_i \alpha_i v_i$, we have $u = (u \cdot w)w$, so u is proportional to w. In this case w belongs to the set $\{\frac{\sum_i \alpha_i v_i}{\|\sum_i \alpha_i v_i\|} \mid \alpha_1, \alpha_2, \alpha_3 \in \mathbb{R} \text{ or } \mathbb{C}\}$. Again, being a two-dimensional set, it will be avoided by a generic choice of w.

In the remainng case, the lines ℓ_1, ℓ_2, ℓ_3 are mutually parallel, i.e., they all have the same direction v. Put, as above, for $i = 1, 2, 3$, $\ell_i = \{p_i + tv\}_t$, and choose p_i so that $p_i \cdot v = 0$. The plane π_0 spanned by p_1, p_2, p_3 is projected to the plane π spanned by the points $p_i^* = p_i - (p_i \cdot w)w$, for $i = 1, 2, 3$ (since p_1, p_2, p_3 are not collinear, they will not project into collinear points in a generic projection), and the three lines project into a common plane if and only if their projections are fully contained in π, meaning that the projection $v^* = v - (v \cdot w)w$ is parallel to π, so it must be a linear combination of p_1^*, p_2^*, and p_3^*. A similar argument to those used above shows that a generic choice of w will avoid the resulting two-dimensional set of forbidden directions.

This completes the proof. □

Note that the "hardest" case in the preceding theorem is $d = 4$. As d increases, it becomes easier to avoid the forbidden two-dimensional sets of directions.

In the analysis in Section 2.2, the goal is to project $\mathbb{R}^d$ onto some generic 3-flat so that non-coplanar triples of lines do not project to coplanar triples. This is easily achieved by repeated applications of Theorem 17, reducing the dimension one step at a time.

Exceptional lines on a singly ruled surface. In view of the proofs of Theorem 10 and Lemma 11, every point on such a surface V is incident to at least one generator. Hence an exceptional (non-generator) line is a line $\ell \subset V$ such that every point on ℓ is incident to a generator (different from ℓ).

Lemma 18. *Let V be an irreducible ruled surface in $\mathbb{R}^3$ or in $\mathbb{C}^3$, which is neither a plane nor a regulus. Then V contains at most two exceptional lines.*

Proof. We use the property, established in Sharir and Solomon [20], that for a line ℓ fully contained in V, the union $\tau(\ell)$ of the lines that meet ℓ and are fully contained in V is a variety in the complex projective space $\mathbb{P}^3(\mathbb{C})$. Moreover, if ℓ is an exceptional line of V, then it follows by [20, Lemma 8] that $\tau(\ell) = V$. (Indeed, $\tau(\ell)$ must be two-dimensional, since otherwise it would consist of only finitely many lines. Since V is irreducible, $\tau(\ell)$ must then be equal to it.)

If V contained three exceptional lines, ℓ_1, ℓ_2 and ℓ_3, then V must be either a plane or a regulus. Indeed, otherwise, by Theorem 10 (whose proof does not depend on the number

of exceptional lines), there exists a one-dimensional curve $\mathcal{C} \subset V$, such that every point $p \in V \setminus \mathcal{C}$ is incident to exactly one line ℓ_p fully contained in V. As $p \in V \setminus \mathcal{C}$ and $\sigma(\ell_i) = V$, for $i = 1, 2, 3$, it follows that ℓ_p intersects ℓ_1, ℓ_2, and ℓ_3.

If ℓ_1, ℓ_2, and ℓ_3 are pairwise skew, p belongs to the regulus $R_{\ell_1, \ell_2, \ell_3}$ of all lines intersecting ℓ_1, ℓ_2, and ℓ_3. We have thus proved that $V \setminus \mathcal{C}$ is contained in $R_{\ell_1, \ell_2, \ell_3}$, and as $R_{\ell_1, \ell_2, \ell_3}$ is irreducible, it follows that $V = R_{\ell_1, \ell_2, \ell_3}$.

If ℓ_1, ℓ_2, and ℓ_3 are concurrent but not coplanar then, arguing similarly, V is a cone with their common intersection point as an apex. Since a (non-planar) cone has no exceptional lines, as is easily checked, we may ignore this case.

Finally if any pair among ℓ_1, ℓ_2, ℓ_3, say ℓ_1, ℓ_2, are parallel then V must be the plane that they span, contrary to assumption. If ℓ_1 and ℓ_2 intersect at a point ξ, disjoint from ℓ_3, then V is the plane spanned by ξ and ℓ_3, again a contradiction.

Having exhausted all possible cases, the proof is complete. $\qquad\square$